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Ultrasonic control

Giacomo Ferrari and Paolo Cardillo, ICITE, Italy, propose the use of ultrasound as a non-destructive method of control applied to cement mortars whose composition is quantified and defined by weight. It is intended as a preliminary tool for minimising manifold factors (such as curing conditions, composition and age) affecting the search for strength/velocity relationships in the definition of possible curves of reference for the characterisation of mortars in types and classes of the main products of the cement industry.

This article presents the interpretive results of a procedure used for estimating Rc standardised compressive strength by using the principal velocity independent variable of ultrasound waves. The variable is obtained from a number of samples that represent four types of cement mortar which are typologically defined using both their ponderal volumetric composition, and the class of strength of the different binders employed.

Experimental programme

The first parameters to be considered while investigating the strength capacity of cement mortars are the type and class of the cement used to prepare the mixes. Currently, there are 25 different types of 'normal cement' on the market. Therefore, the choice of the cement type used for the preparation of the specimens under investigation was limited to the two types most frequently used in the construction industry. These were:

- Composite Portland cement (PTL): ENV 197-1 CEM II.
- Blastfurnace cement (AF): ENV 197-1 CEM III.

The strength classes associated with the types of cement selected for the preparation of reference mortars have been identified as follows:

- Classes 32.5, 42.5, 52.5 for composite Portland cement.
- Class 32.5 for blast furnace cement.

All mixes of reference mortars were prepared using standardised sand from the Torre del Lago quarry (Pisa, Italy), mixed using a water/cement ratio of 3:1, in compliance with the recommendations of Point 6 of standard UNI EN 196-1. This has also been adopted for the composition (water/cement ratio 0:5), dosage, mixing of mortars, and then preparation, shakeout and seasoning in water of the samples.

With regard to the preparation of subsequent tests to determine the principal velocity of ultrasonic waves and for the specification of standardised compressive strength, the experimental programme took into account and referred to four different cement mortars. These were all characterised by weight using the same aggregates, and the same values of aggregate/cement ratio (A:C = 0.5), but were individually diversified according to the type and class of cement used in the mixture. From these mortars, hereafter referred to as M1 (A), M1 (B), M1 (C), M1 (D), 365 prismatic samples were manufactured (with dimensions 40 mm x 40 mm x 160 mm) have been produced. After curing for 28 days in water, these specimens were used for the execution of the standardised compressive strength tests, after determining the

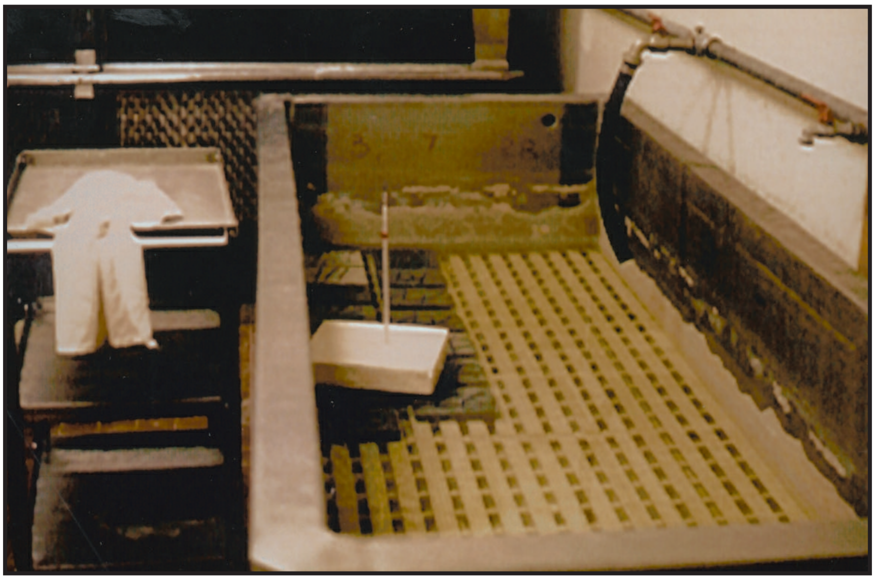

Figure 1. Cement mortar samples maturing in water.

Table 1. The test programme for characterising strength capacity and determining the principal velocity of elastic waves transmitted to the samples

M1(A)	CEM 325 AF	ENV 197-1	CEM III 32.5	30	specimens
M1(B)	CEM 325 PTL	ENV 197-1	CEM II 32.5	94	specimens
M1(C)	CEM 425 PTL	ENV 197-1	CEM II 42.5	159	specimens
M1(D)	CEM 525 PTL	ENV 197-1	CEM II 52.5	82	specimens

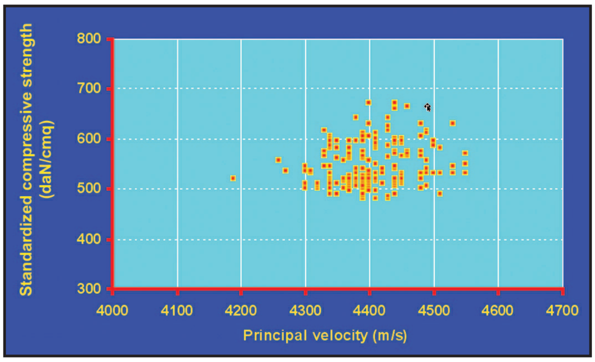

Figure 2. The scatter diagram for mortar M1(C).

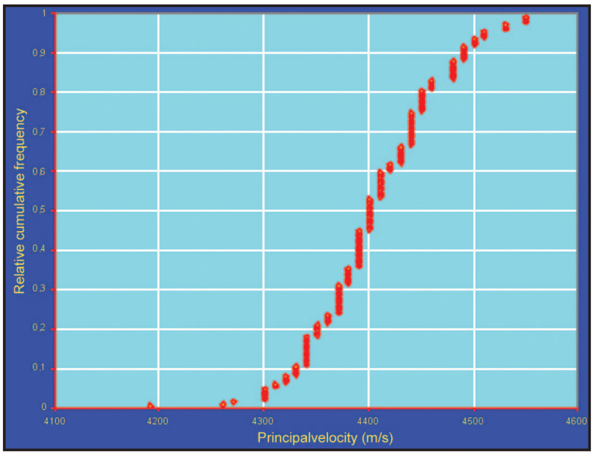

Figure 3. Distribution of the relative cumulative frequency.

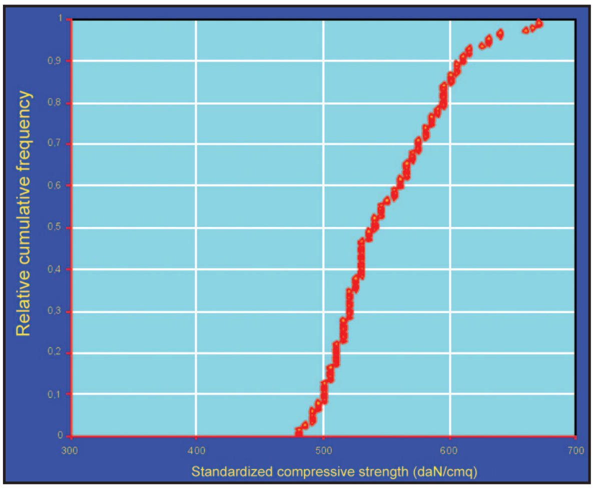

Figure 4. Distribution of relative cumulative frequency for the principal velocity of ultrasonic impulses of mortar sample M1(C).

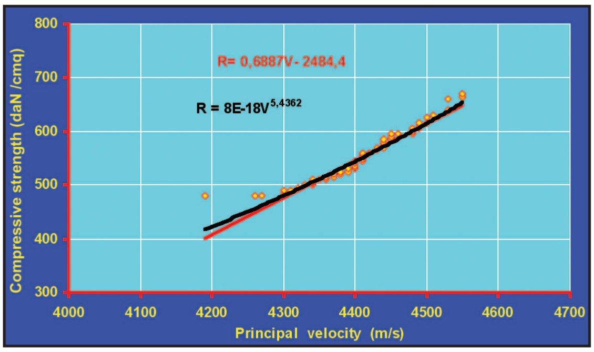

Figure 5. Relative cumulative frequencies for the standardised compressive strength values obtained on each individual sample.

velocity of propagation of ultrasonic impulses using ultrasonic impulses in compliance with standard UNI 9524.

The test programme for the characterisation of strength capacity and the determination of the principal velocity of the elastic waves transmitted to the samples, was divided into four series, as shown in Table 1.

The measurement of velocities in the cement mortar samples was carried out using a portable ultrasonic instrument known as Mod. 58-E0049/A manufactured by Controls SrL, Italy. This measures the generation of impulses calibrated at regular intervals. The Console 'MCC8' Series Mod. 50-C8222 and the Twin Column Frame Mod. 65-L1301/*', also from the same manufacturer, were used to determine the standardised compressive strength, as specified in standard UNI EN 196-1. The twin column frame has two test chambers, with 250 kN and 15 kN capacities, and is fitted with electronic load cells.

Interpretation of test results

The numerical results (vi, Rci) obtained in the single tests of the experimental programme have been considered and treated as representative statistical samples of the four types of cement mortar [M1 (A), M1 (B), M1 (C), M1 (D)]. These were selected to obtain an analytical description of the most probable links between the two physical properties: standardised compressive strength Rc and principal velocity of longitudinal waves Vp.

The statistical analysis of random variables of principal velocity Vp and standardised compressive strength Rc requires the calculation of the main statistic parameters estimated using samples extracted from a respective population that is assumed to have a normal distribution.

A number of values were estimated for the individual random variables (Vp main velocity of the propagation and Rc standardised compressive strength) of the four samples, including the mean, standard deviation, variation coefficient the percentage ratio between standard deviation and the mean, characteristic values or fractiles of rank 0.05 Vp and Rc, and finally the maximum and minimum values. The difference between the minimum and maximum values indicates the extent of the respective samples.

Scatter diagrams were constructed using the data acquired from the respective sets of specimens prepared for the physical characterisation of the four mortar specimens. Figure 2 shows the scatter diagram for mortar M1(C). This diagram represents the original experimental points (Vpi, Rci) identified for M1(C).

Figure 3 presents the relative cumulative frequency for each individual statistical sample, characterised either by the ultrasonic propagation velocity random variable Vp or by standardised compressive strength Rc.

Figure 4 shows the distribution of relative cumulative frequency for the principal velocity of ultrasonic impulses Vp of mortar sample M1(C). Similarly, Figure 5 shows the relative cumulative frequencies for the Rc standardised compressive strength values obtained from each individual sample. Here, relative cumulative frequency of the individual sample data represents the ratio between the order number of the data itself. The data is classified according to an increasing order, and the corresponding dimension of the sample increased by one unit.

The cumulative frequency curves that were obtained from these diagrams represent an approximate estimate of the probability functions Pi (Vp) and Pi (Rc) of the random variables of principal velocity and standardised compressive strength Rc of the four reference cement mortars.

Because the parameters of the mean and the mean quadratic deviation of each distribution were assumed normal, and have been estimated, it is now possible to make an analytical representation of the probability functions (sometimes also called distribution functions) Pi (Vp) and Pi (Rc). These functions would allow the analysis of the statistical variability of principal velocity Vp and of standardised compressive strength Rc for each cement mortar under consideration. However, there are more particular and representative statistical quantities, which are characteristic of the whole of the N couples of values of the two-dimensional random variables (Vpi and Rci). Therefore, the analysis has been focused primarily on the connection between the two random variables of principal velocity and standardised compressive strength distributed in the plane V, R.

Abandoning the idea of constructing the statistics of the two random variables Rc and Vp, calculating and interpreting the correlation coefficient of Pearson gives the following equation:

$$r = \frac{\sum_{i=1}^{n}(R_i - \bar{R})(V_i - \bar{V})}{\sqrt{\sum_{i=1}^{n}(R_i - \bar{R})^2 \sum_{i=1}^{n}(V_i - \bar{V})^2}}$$

This equation is dimensionlessly defined as the ratio between the covariance and the outcome of the mean quadratic deviations of the two random variables of principal velocity and standardised compressive strength. The ratio was calculated on the four specimens of original mortar [M1 (A), M1 (B), M1 (C), M1 (D)] and on the corresponding fictitious samples obtained by ordering the couples of data (Vi, Ri) that have the same value of relative cumulative frequency or according to other terms of probability. The results for the four samples are shown in Table 2.

Table 2. The correlation coefficient of Pearson for the four mortar samples

Mortars typology	M1 (A)	M1 (B)	M1 (C)	M1 (D)
Value original	0.0509	0.5109	0.1820	0.5343
Value fictitious	0.9817	0.9261	0.9704	0.9907

Table 3. Recapitulation of the analytical expressions R= f (V) obtained from the analysis of regression conducted on the four specimens of mortar

Mortar type	Regression line type (linear/power)	r^2
M1(A)	R = -2580.8 + 0.69562V	0.964
	$R = 3.144\ e - 24\ V^{7.1868}$	0.961
M1(B)	R = -1132.3 + 0.36632V	0.858
	$R = 9.0978\ e - 11\ V^{3.4915}$	0.862
M1(C)	R = -2484.4 + 0.68870V	0.942
	$R = 8.4993\ e - 18\ V^{5.4362}$	0.948
M1(D)	R = - 2700.0 + 0.75937V	0.981
	$R = 8.9712\ e - 12\ V^{5.1745}$	0.983

Results

Given the meaning of the linear correlation coefficient of Pearson as a measure of the linearity of the existing link between the variables of principal velocity and standardised compressive strength (strictly linear for r = ± 1, no correlation for r = 0) and of the meaning of positive direct correlation for r> 0, it is possible to draw the first qualitative results:

- For all examined samples, the existing correlation between the principal velocity Vp and the standardised compressive strength is positive or direct (r > 0). This observation implies that statistically, as principal velocity increases, standardised compressive strength also increases.
- The link between the couples (vi, Ri) of the velocity values and compressive strength random variables tends to be linear (r= 1) if, acting on fictitious samples, the data of velocity and standardised compressive strength are ranked according to an increasing order, with the same value as the respective probability function [P (Vpi)= P (Rci)].

These qualitative results led to further statistical analysis in order to investigate the functional relationships between the two variables of velocity and strength. This analysis was carried out by studying regression of the data collected from the four mortar samples. The method of regression was employed in the two-dimension distributions not to adapt a law of probability to the observations, but rather to expressively determine a statistic link between the two random variables of velocity and compressive strength in a simple and practical way.

Once it has been established which of the two variables will be used as the independent variable in the functional empirical connection, together with which type of regression to adopt (R on V), a priori choice of the type of curves of regression to adopt was made. These were as follows:

- Linear $R= C_0 + C_1 V$
- Power $R = C_2 V^{C3}$

(Where R and V are the standardised compressive strength and the principal velocity respectively, while the individual coefficients (C_0, C_1, C_2, C_3) of the respective representative curves of the mechanical characteristics of the mortars are individually determined for each curve of regression. This is achieved by reducing the sum to the minimum:

$$s = \sum(R_i - R_{is})$$

of the squares of the deviations between the observed values of the variable of standardised compressive strength Ri

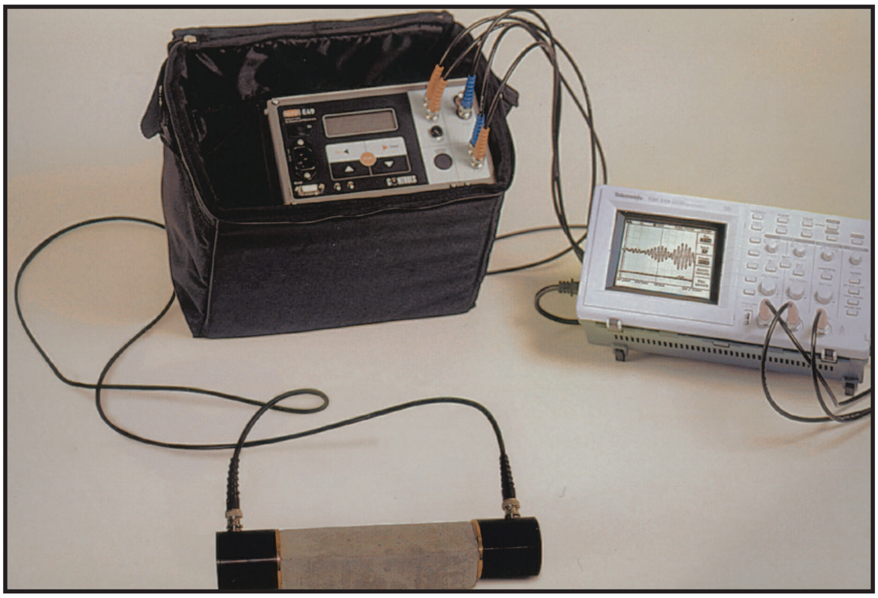

Figure 6. The portable ultrasonic test equipment (manufactured by Controls SrL) used in the laboratory.

Figure 7. The test equipment (manufactured by Controls SrL) used to determine standardised compressive strength in the laboratory.

and the corresponding Ris values that, with an equal value of principal velocity V, can be read on the regression curve.

The results of this analysis are shown in Table 3. For each statistical sample of the investigated mortars, ordered with N couples of points (Ri, vi) that take the same relative cumulative frequency, the analytical expressions of the curves of regression R = f (V) have been shown in order to describe the functional dependence of the standardised compressive strength on the ultrasonic velocity in the different examined mortars.

Figure 5 shows an example of the trends of the lines of linear regression shown in Table 3. For each determination it is important to notice the excellent adaptation of the lines to the data of the different samples that represent the different cement mortar typologies. This result is also confirmed by the values of the coefficient of determination R^2i very close to the unit. This is the quadratic expression of the coefficient of correlation ri.

Conclusion

This discussion has underlined that ultrasonic investigation, along with statistical analysis, is intended as a non-destructive method of control to be applied to cement mortars to measure the strength capacity of the mortars themselves.

This method is not only interesting because of the possibility it offers to forecast compressive strength when the specific calibration curve of the analysed mortar has been traced, but also ad chiefly because of the possibility offered to appraise the curing degree of mortars over time. This value is measured by the increase of the velocity of propagation which can be measured in the mortar specimens.